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The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S.

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ABSTRACT

The global demand for wood pellets used for energy purposes is growing. Therefore, increased amounts of wood pellets are produced from primary forestry products, such as pulp wood. The present analysis demonstrates that substantial amounts of alternative, low-value wood resources are available that could be processed into wood pellets. For three resources, test batches have been produced and tested to qualify for industrial pellet standards. These include: primary forestry residues from premerchantable thinning operations, secondary forestry residues from pole mills and post-consumer wood wastes from discarded wooden transport pallets. The total wood potential of these resources in the southeast of the U.S. (Florida, Georgia, North Carolina, South Carolina), was estimated to be 1.9 Tg y^{-1} (dry) available at roadside (excluding transport cost) for 22 \$ Mg^{-1} (dry) increasing to over 5.1 Tg y^{-1} at 33 \$ Mg^{-1} (dry). In theory, 4.1 Tg y^{-1} pellets could be produced from the estimated potential. However, due to the geographically dispersed supply of these resources, the cost of feedstock supply at a pellet plant increases rapidly at larger plants. It is therefore not expected that the total potential can be processed into wood pellets at costs competitive with those of conventional wood pellets. The optimal size of a pellet plant was estimated at between 55 Gg y^{-1} and 315 Gg y^{-1} pellets depending on the location and feedstock supply assumptions. At these locations and plant sizes, pellets could be produced at competitive costs of between 82 \$ Mg^{-1} and 100 \$ Mg^{-1} pellets.

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1. Introduction

Concerns on energy supply security and climate change have increased the demand for biomass used for bioenergy purposes including liquid biofuels, such as ethanol and biodiesel, and solid biofuels, such as wood chips and wood pellets. Wood biomass is still mainly used traditionally, i.e. for local cooking and (low temperature) heating. However, policies targeted to renewable energy generation, have driven the demand for solid biomass for industrial uses including electricity generation in standalone or co-firing in coal power plants, combined

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heat and power and district heating, especially in the European Union (EU-27). In contrast to residential sectors, industrial uses of solid biofuels in the EU-27 are highly import dependent [1,2]. Trade of solid biofuels and in particular wood densified into wood pellets, has therefore grown rapidly. In the EU-27, the import of wood pellets increased from 1.9 Tg in 2009 to 4.6 Tg in 2012 [3] and this trend is likely to continue in the future. By 2020, the global demand for wood pellets is estimated to be between 45 Tg and 80 Tg with imports of wood pellets to the EU-27 in the range of 15 Tg to 30 Tg depending on policy developments, the deployment of bioenergy and the mobilization of domestic resources [2–4].

Western Canada (British Columbia) and the southeast of the U.S., have become key exporting regions for wood pellets mainly driven by the demand in the EU-27. In the southeast of the U.S. (Florida, Georgia, North Carolina, South Carolina), over 3.6 Tg y^{-1} wood pellet production capacity is currently online (44% of the total capacity in the U.S.) and almost 3.0 Tg y^{-1} wood pellet production capacity is under construction or proposed [5,6]. By-products from wood processing industries, such as saw dust, are still the primary source of wood pellet production. However, the sawmilling industry has retrenched due to the sharp decline in demand for solid wood timber products. The demand for solid wood timber products in the U.S. reduced by half from 202 hm^3 in 2005 to 110 hm^3 in 2009 mainly a result of the economic crisis and its effect on the housing market [7]. This has resulted in an imbalance between supply and demand of secondary wood residues [8] and in combination with the decreased demand for wood from primary sources, has increased the production of wood pellets from primary forestry products, for example pulp wood.

Several NGOs and other actors have criticized the uses of primary forestry products (mainly pulp grade wood) for energy purposes due to ecological concerns and possible reduced or even negative greenhouse gas (GHG) mitigation performances. While increasing amounts of primary forestry products are used, there are still low-value wood sources available that are currently unused or used inefficiently, (e.g. in low temperature heating systems). Possible reasons that these wood sources are not used for the production of wood pellets are that they do not comply with the high quality standards for wood pellet production, or that they are too expensive to mobilize compared to conventional wood sources. Examples of these unconventional wood sources include forest biomass (both primary and secondary residues) and urban wood wastes. Urban wood waste is the collective term for the woody component of municipal solid waste (MSW) and construction and demolition (C&D) wood. In the U.S., over 72 Tg (dry) wood could be available for bioenergy production for under 44 \$ Mg^{-1}, including primary forestry residues (46%), ‘other removal residues’ (15%), secondary forestry residues from saw mills (9%) and urban wood wastes (29%), but excluding roundwood and pulp wood [9]. Part of this material could also become available for the production of wood pellets if the biomass material is properly collected and adequate preprocessing techniques are used. Processing of these low-value wood resources by pelletization, results in a high value energy commodity that can be transported over long distances and used in efficient conversion plants. However, for many of these resources, the logistics and removing or avoiding contaminants, e.g. sand, are still a major challenge.

This chapter analyses the economic potential of wood pellet production from alternative wood sources in the “wood fiber basket” region of the southeast of U.S. including the states of Florida, Georgia, North Carolina and South Carolina. The emphasis of this study is on the current supply potential and cost of biomass, but conservative medium term (2020) scenario projections are also included. The results are expressed in U.S. dollars (2012).

2. Methods and data

2.1. Wood resources selection

The present analysis focused on wood resources that are suitable for the production of wood pellets and that are currently underutilized due to abundance of supply and lack of markets, used inefficiently, e.g. used as boiler fuel, or not used and discarded as waste. First, actual wood samples were collected in the state of Georgia (U.S.) [10]. Three wood fiber sources were selected for further analysis from the collected wood samples as depicted in Table 1. The selection was made based on the following criteria: ash contents of maximum 2% as required by industrial pellet customers [10], moisture content, possible contaminations, availability, distance to pellet plants and demand. Only wood resources were considered with low to moderate demand and used only for low-value purposes, e.g. furnace fuel, or discarded as waste.

Pallets are flat structures that improve handling and stability of goods during transport, handling and storage. Pallets are constructed from different materials including metals and plastic, but the most common are wooden pallets and about 90% of all pallets are made from wood, predominantly hardwood [11]. Most pallets remain in circulation and change owners several time before they are taken out of service. At the end of the life cycle, the majority of transport pallets are either collected by pallet recycling companies or collected at landfill areas. Wood chips from discarded wooden transport pallets were selected because they are a relatively clean type of post-consumer residue (tertiary biomass) that can meet the quality specifications of the wood pellet plant if processed correctly. Pallet recycling companies already separate different qualities of pallets and remove possible contaminants (plastics, paper) to produce wood chips for mulch, fuel and animal bedding. Nails are removed from ground pallets using magnets. Currently, most pallet recycling companies reject pallets that cannot be repaired or recycled because there are few markets for chipped pallets.

Wood residues from primary wood processing industries are the preferred source of wood fiber for wood pellet production because they do not require major resizing and are relatively dry and clean. However, 98% of these wood residues are already utilized in the U.S. [9]. Still, the demand for wood residues from pole production mills is identified to be low in Georgia [10]. Utility pole mills process pine trees into standard sizes by debarking, and sizing (cutting to length and circumferences). The by-products are a mixture of clean wood and bark and therefore difficult to use in existing markets [10]. Pole

Table 1 – Selected wood resources and properties [10].

	Name	Description	Ash content (% w/w)	Moisture content (% w/w)[a]
1	Discarded pallets	Wood waste: chipped wooden transport pallets that cannot be recycled (hardwood chips)	0.9–1.5	23.3 (23.3–24.8)
2	Pole peelings	Sawmill residues: pole mill residues (ground/chipped softwood)	0.5–1.3	17.0 (15.7–18.9)
3	Unmerchantable forest biomass	Forest residues: wood chips produced from land clearing and premerchantable harvest forest management activities (hardwood chips)	1.4–2.0	Hardwood: 42.9 (35.5–42.9) Softwood[b]: 50.0

[a] Moisture content assumed in cost analyses (transportation and drying) and between brackets, the ranges found in test samples.
[b] No test samples for softwood, assumed 50%.

mill residues are mainly used in the pole mills or sold as furnace fuels [13,14].

Forest residues that are generated during precommercial thinning operations, to improve the quality of the remaining stands, or during clearing of timberland for other land uses or replanting. The wood removed includes unmerchantable, poor shaped or undesired types of stems, small (hardwood) trees, limbs, barks and tops and is also referred to as 'other removals' [9,15,16]. Due to the nature of these forest management activities, 'other removals' are a heterogeneous source of wood with potentially high ash contents (sand, bark, leaves) that are not always economically feasible to mobilize [9]. Nevertheless, the tested samples demonstrate that pellets could be produced with ash contents below 2% (Table 1). These unmerchantable forest residues are currently left (and burned) in the forest or chipped and used as a furnace fuel, of which the fuel demand is not constant [10]. It is unknown how much is used and how much is left unused in the forest.

2.2. *Technical and economic potential*

The present analysis used the guidelines of the Biomass Energy Europe – Best Practices and Methods Handbook [17] to determine the potential of the selected wood resources. First, the technical potential of the biomass resources was determined taking into account technical constraints, e.g. as are implied by collection techniques, as well as existing uses of the selected wood sources [18]. Wood fibers used for materials, e.g. mulch or animal bedding, were considered unavailable for wood pellet production. Some of the wood resources assessed in this study were already used for bioenergy purposes, mainly as a low grade furnace fuel. At the same time, many low-grade wood sources are currently unused because of the availability of better alternatives [10]. It was therefore assumed that, when new pellet markets develop, these wood fiber sources would be reallocated driven by the higher market value as a feedstock for pellet production compared to furnace fuels [19]. Finally, a cost-supply method was used to calculate the total cost of pellet production as explained in Section 2.3.

2.2.1. *Unmerchantable forest residues*

The 'unmerchantable forest residues', as defined in the present analysis, are consistent with the forest biomass category 'other removals' from the U.S. Billion Ton study [9]: "*Other removal residues are the unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing. Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.*" Data of 'other removals' (in volume wood generated) are collected by the U.S. Department of Agriculture Forest Service in context of the Forest Inventory and Analysis (FIA) program and reported in the Timber Product Output (TPO) database. Data are available for every two years up to 2009 by wood class (hardwood and softwood), county, and land ownership (public or private) and growing and non-growing stock volumes removed [20]. The main limitation of the TPO database is that it does not distinguish between 'other removals' that are produced from land clearing activities and 'other removals' from precommercial thinning operations. Although the production of

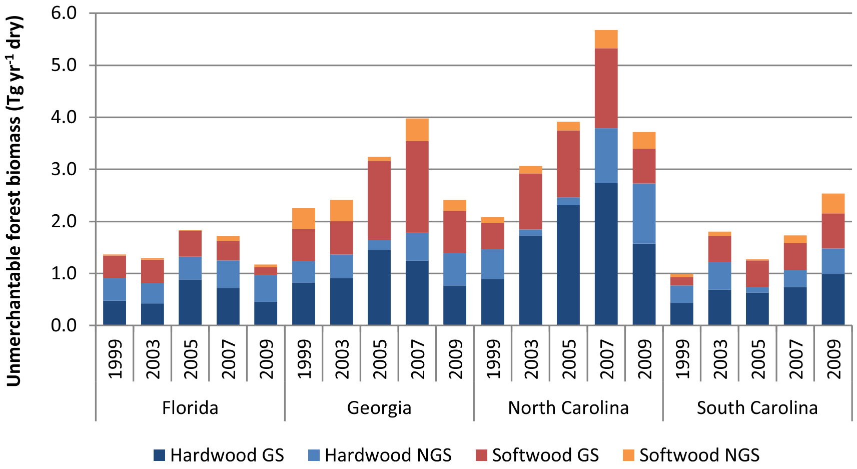

Fig. 1 – Unmerchantable forest biomass produced in the southeast of the U.S. 1999–2009 by state, wood type (hardwood, softwood) and source (GS: growing stock, NGS: non-growing stock) [20] in Tg y^{-1} dry wood (moisture fraction hardwood 43%, softwood 50%). Data for 2001 was not available for all states in the selected region.

'other removals' is not driven by demand markets, the inclusion of 'other removals' from land clearing makes the carbon saving potential questionable when used for bioenergy [21].

Pre-commercial thinning operations, but especially land clearing activities vary in time and region. The data of the TPO show that the amount of 'other removals' generated have been fluctuating heavily in the selected region (Fig. 1). Therefore, average removals in the period 1999 to 2009 were assumed to represent the current theoretical availability of 'other removal residues'. Considering that 'other removals' are difficult to recover, a recovery rate of 50% was assumed similar to the updated Billion Ton study [9] to calculate the technical potential (equation (1)) [17]. The lowest and highest generation of 'other removals' in the period 1999 to 2009 in the individual states were assumed to represent lower and upper limit ranges.

$$TCP_{ORR_{x,y}} = THP_{ORR_{x,y}} * AR \tag{1}$$

$TCP_{ORR_{x,y}}$: technical potential of 'other removal residues' in county x in year y, (Mg y^{-1})
$THP_{ORR_{x,y}}$: theoretical potential of 'other removal residues' in county x in year y, (Mg y^{-1})
AR: average recovery rate of 'other removal residues'

There is limited information available on the cost of harvest and collection and roadside prices of 'other removals' [9,22]. Similar to the updated Billion Ton Study [9], the following assumptions have been made to estimate the economic potential of 'other removals':

- 33% of the technical potential is available at roadside for 22 $ Mg^{-1} (dry)
- 67% of the technical potential is available at roadside for 33 $ Mg^{-1} (dry)

These cost estimates are consistent with Walsh [22] who estimates break even cost of collection and chipping of 'other removals' using the regional distribution of non-growing stock harvest costs. At 33 $ Mg^{-1} or less, Walsh [22] estimated that 36% of total 'other removals' to be available compared to 33% in the present analysis at similar cost levels.

2.2.2. *Secondary residues: pole peelings*

The amounts of by-products produced in pole mills and their current uses in the southeast of the U.S. are collected by the Timber Product Output group of the USDA-Forest Service. For reasons of confidentiality, these figures are reported collectively with the residues produced in 'other primary wood processing mills' in the TPO database. For the present analysis, the amount of by-products from pole mills were therefore quantified based on the primary output of poles, posts and pilling mills that were reported at the county level in the TPO database and equation (2) [17]. The residue factors in Table 2 were based on forest production conversion factors (ratio of raw material input to product output) for pole mills in the southeast of the U.S. that were available at the USDA Forest Service [13]. The ranges for wood residues were based on the minimum and maximum conversion factors for pole, post and piling mills found in the UNECE region. The UNECE region covers Europe, North America and parts of Asia [23].

$$TCP_{res_{x,y}} = FP_{x,y} * RF_{bark,wood} - USR_{bark,wood\ x,y} \tag{2}$$

$TCP_{res_{x,y}}$: technical potential of pole mill residues in county x and year y

Table 2 – Residue factors of poles, posts and piling mills from softwood [13,23].

Residue	Unit	Residue factor
Bark[a]	m^3/m^3	0.28
Wood	m^3/m^3	0.20 (0.15–0.24)[b]

[a] Average pole volume = 0.375 m^3/pole, moisture mass fraction = 17%, wood density = 0.589 Mg/m^3.
[b] Ranges between brackets are based on the lowest conversion factor (most efficient) for post, poles, pilings (1.10 for utility poles in Ireland [23]) and highest conversion factor (least efficient) for post, poles, pilings (1.75 for pilings in Slovakia [23]).

$FP_{x,y}$: volume of pole production in county x in year y ($m^3\ y^{-1}$)

$RF_{bark,wood}$: residue factor for wood and bark by volume of the produced poles in county x in year y ($m^3\ y^{-1}$)

$USR_{x,y}$: volume of residues used for material production (e.g. wood chips and bark consumed by board industry) or internally utilized by the sawmill as energy source, in county x in year y ($m^3\ y^{-1}$). It was assumed that all wood residues produced in pole mills could be reallocated to wood pellet production and all bark residues are used internally by the pole mills.

2.2.3. *Tertiary biomass: discarded transport pallets*

New pallets are shipped to pallet customers, mainly product manufacturers that use these pallets to ship loads to wholesalers or distribution centers. Pallets are also directly sold to distribution centers for the purpose of creating mixed loads [12]. Pallets are either used in closed loop (pooled) and open loop (non-pooled) [11]. Non-pooled pallets change owner with the transported cargo and generally have a short lifetime whereas pooled pallets circulate in a closed system and are built to higher specifications with thicker and higher grade boards, better nails and are generally used multiple times, either with or without repair [12,24]. At the end of life, pallets are either recycled, downcycled (i.e. used for lower grade purposes), or landfilled in MSW and C&D landfills [11,25]. Recycled pallets are either re-used without repair, repaired or dismantled for repair material. Downcycled pallets are mainly ground and used for colored and uncolored landscape mulch, animal bedding and energy (furnace fuel). Although the market value for landscape mulch is currently higher than the market value for energy, the use of ground pallets for wood pellet production could increase the market value of energy over the current use as a low-grade furnace fuel. In the present analysis, we considered pallets that are used for material markets (mulch and animal bedding) to be unavailable for wood pellet production. The remaining fraction of downcycled pallets and pallets that are currently landfilled are assumed to be available for wood pellet production.

To estimate the potential of ground pallet material for pellet production in the southeast of the U.S., the present analysis uses survey data of the wood container and pallet manufacturing industry in the U.S. (NAICS code 321920) as collected every five years by Virginia Tech. The most recent data available are from 2006 and based on the responses of 450 out of 2580 unique firms contacted in the U.S.. These firms represent 590 production facilities in the U.S. [26]. The results are extrapolated by region in the U.S. based on employment numbers. The employment share in the wood container and pallet manufacturing industry in southeast of the U.S. (13% of the U.S. total [27]) was used to estimate the potential in the relevant states in the present analysis.

Fig. 2 shows the flow diagram of GMA (Grocery, Manufacturers, Association) pallets, the most common type of pallet, and the 2006 survey data from Virginia Tech used to estimate the potential of discarded pallets. The values between brackets are for the south of the U.S. that covers the states in the present analysis. In the U.S., between 2 and 4 billion

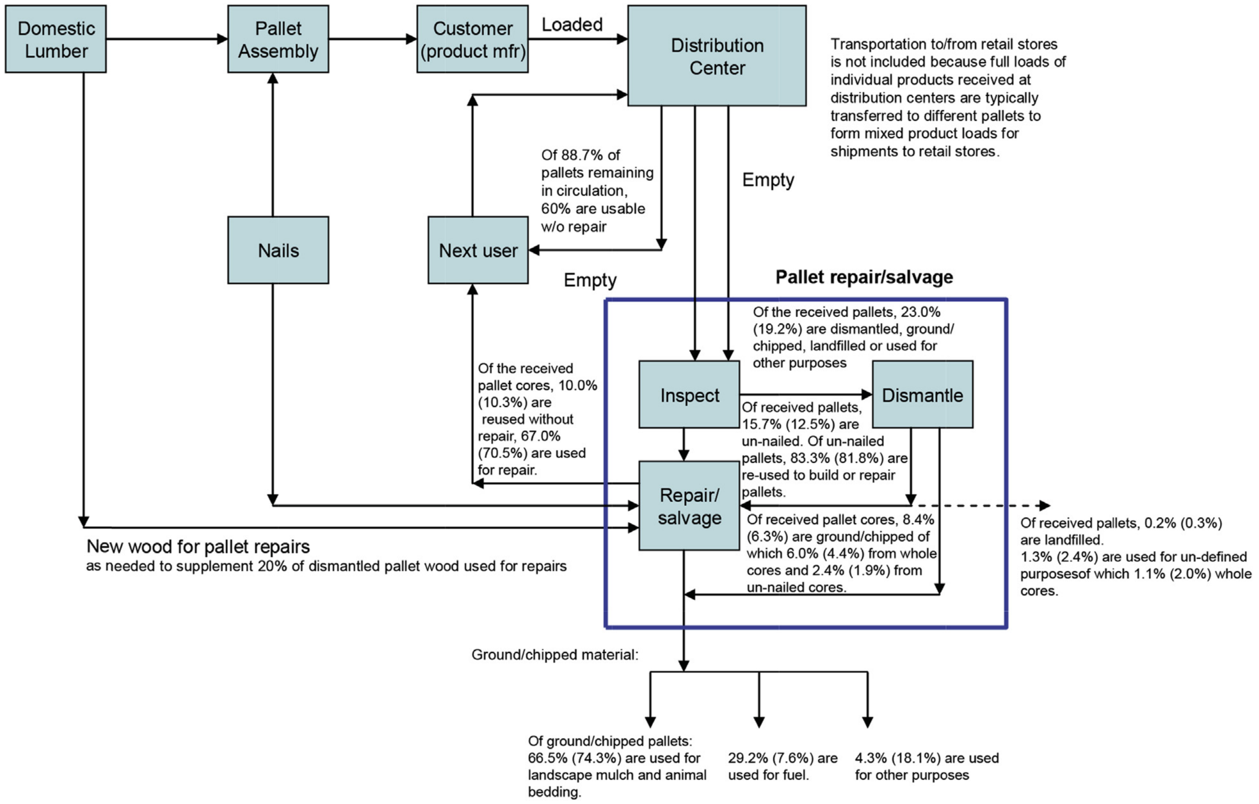
Domestic Lumber
Pallet Assembly
Customer (product mfr)
Loaded
Distribution Center
Transportation to/from retail stores is not included because full loads of individual products received at distribution centers are typically transferred to different pallets to form mixed product loads for shipments to retail stores.
Of 88.7% of pallets remaining in circulation, 60% are usable w/o repair
Empty
Nails
Next user
Empty
Pallet repair/salvage
Of the received pallets, 23.0% (19.2%) are dismantled, ground/chipped, landfilled or used for other purposes
Of the received pallet cores, 10.0% (10.3%) are reused without repair, 67.0% (70.5%) are used for repair.
Inspect
Dismantle
Of received pallets, 15.7% (12.5%) are un-nailed. Of un-nailed pallets, 83.3% (81.8%) are re-used to build or repair pallets.
Repair/ salvage
Of received pallet cores, 8.4% (6.3%) are ground/chipped of which 6.0% (4.4%) from whole cores and 2.4% (1.9%) from un-nailed cores.
Of received pallets, 0.2% (0.3%) are landfilled.
1.3% (2.4%) are used for un-defined purposesof which 1.1% (2.0%) whole cores.
New wood for pallet repairs
as needed to supplement 20% of dismantled pallet wood used for repairs
Ground/chipped material:
Of ground/chipped pallets: 66.5% (74.3%) are used for landscape mulch and animal bedding.
29.2% (7.6%) are used for fuel.
4.3% (18.1%) are used for other purposes

Fig. 2 – Flow diagram for GMA pallets, adapted from Franklin Associates [12] with data for all wooden pallets in the U.S. and for the south of the U.S. between brackets. Data from Bush and Araman [26].

wooden transport pallets are in use every day that are either new, re-used without repair or re-used after repair [28,29]. In 2006, 441 million pallets have been produced from new wood in the U.S. consuming 11 hm^3 of hardwood and 6 hm^3 of softwood. Furthermore, 460 million pallets were collected by pallet recyclers/companies in the U.S. in 2006 and re-used or remanufactured into 321 million pallets from the recovered wood [26]. Wood pallets are collected by recycling companies if they need to be repaired, if they can be used for recycling or if they have no functional use [24]. Depending on the quality of the collected pallets, recyclers either pay for the collected pallets ($ 1 to $ 2 per pallet) if they can be re-used without repair, collect them without payment if they need to be repaired or request a tipping fee for the collection of pallets that need to be ground or require much repair [24]. Pallet grinding is considered a required activity to process unwanted material and most pallet recycling companies avoid as much as possible receiving pallets they cannot recycle or reuse [24].

The most recent data for pallets disposed in landfills are from 1998 [25]. In that year, 178 million pallets were disposed in landfills of which 38 million pallets were recovered and used for mulch (30%–44%), landfill cover (12%–16%), fuel (15%) or re-used as pallets (10%–22%). The remaining fraction was still landfilled in 1998 of which 66% in C&D and 84% in MSW landfills. Many programs have been initiated to reduce landfilling of pallets. In North Carolina, Act 1465 came into effect in 2009, banning the disposal of wood pallets in MSW landfills [30]. Furthermore, landfills have started recovery operations and offer lower tipping fees for sorted loads to improve the recoverability of these pallets [25]. Although uncertain, it was assumed I the present analysis that around 100 million pallets are still landfilled each year in the U.S. of which 13 million (13%) are landfilled in the southeast of the U.S.. Furthermore, 2.4 million pallets were estimated to be available at pallet recycling companies in the southeast of the U.S..

2.3. *Cost-supply curves and pellet production*

2.3.1. *Transport and handling*

The cost of biomass transport from the supply origin to the pellet plant includes fixed handling cost (loading and unloading) and variable transportation cost. These costs can add substantially to the total feedstock cost delivered at the pellet mill depending on the hauling distance, the moisture content and the bulk density of the feedstock. A Geographic Information Systems (GIS) based tool was used running in the Network Analyst extension of ESRI's ArcGIS® 10.1 with street map vector data for North America [31] to estimate the cost of feedstock supply. Similar to Staudhammer et al. [32], the routes were optimized for shortest travel time. Furthermore, the following assumptions were made:

- Variable transport cost (truck): 0.031 $ km^{-1}
- Fixed handling cost (loading/unloading): 2.00 $ Mg^{-1} (ar) (ar: as received)
- Empty returns: yes
- Speed: 75% of the road specific allowed speed
- Bulk capacity (truck): 18 Mg (ar)
- Fuel economy (diesel): 0.39 L km^{-1}
- Fuel cost (diesel): 0.93 $ L^{-1}

2.3.2. *Pellet production*

The wood pellet production process covers all operations required to convert raw biomass feedstock into industrial wood pellets, including storage, drying, grinding and densification. The cost of pelletization can vary substantially between locations [33] and the type of process used [34]. The capital requirements in the present analysis were based on studies for North America [35,36]. The final energy requirements of the pellet plant (electricity) are based on European studies [33,37], but were considered representative for the pellet plant capacities and locations in the present analysis.

Most of the equipment used in a pellet production plant is difficult to scale up and require multiple parallel systems. For example, most pellet plants include several pellet mills, cyclones and grinders. Nevertheless, a scale factor of 0.7 was assumed in the present analysis based on Pirraglia et al. [35], to calculate the capital invest for the required plant size using the power law formula (equation (3)). Capital investments were annualized using equation (4) and a discount rate of 6% [35]. The lifetime is equipment specific ranging from 10 years for the hammer mills to 20 years for office buildings [35]. The specific capital costs of larger pellet plants are lower due to economies of scale. However, these pellet plants require a larger sourcing area for the supply of wood materials which implies higher hauling cost compared to smaller pellet plants.

$$\mathrm{Inv} = \mathrm{Inv}_{\mathrm{ref}} * \left(\frac{P}{P_{\mathrm{ref}}}\right)^{0.7} \tag{3}$$

$$\mathrm{CRF} = \frac{i}{1-(1+i)^{-L}} \tag{4}$$

Inv = capital investment of the pellet plant
$\mathrm{Inv}_{\mathrm{ref}}$ = capital investment of the reference pellet plant
P_{ref} = size of the reference pellet plant (Mg pellets y^{-1})
P = size of the pellet plant (Mg pellets y^{-1})
CRF = Capital Recovery Factor
L = utilization period (years)
i = interest rate

2.3.3. *Cost-supply curves and total cost*

The supply of unmerchantable forest residues, pole mill residues and discarded pallets, is geographically scattered. There are only a limited number of pole mills and pallet recycling companies in the southeast of the U.S. and unmerchantable forest residues are being generated at relatively small land areas that are geographically scattered throughout the region (Fig. 3). In the selected four states, 11 pellet production plants were identified that, at the time of the study, were operational (5 plants), under construction (1 plant) or proposed (5 plants) with pellet production capacities ranging from 32 Gg y^{-1} to 750 Gg y^{-1} [6]. These locations were assumed to represent the candidate locations to process the selected feedstocks. The specific designs or capacities of these pellet plants were not considered in the present analysis. For example, the infrastructure of some of these pellet plants is designed to process dedicated feedstocks such as pulp wood and might not be able to process the selected wood sources in this study.

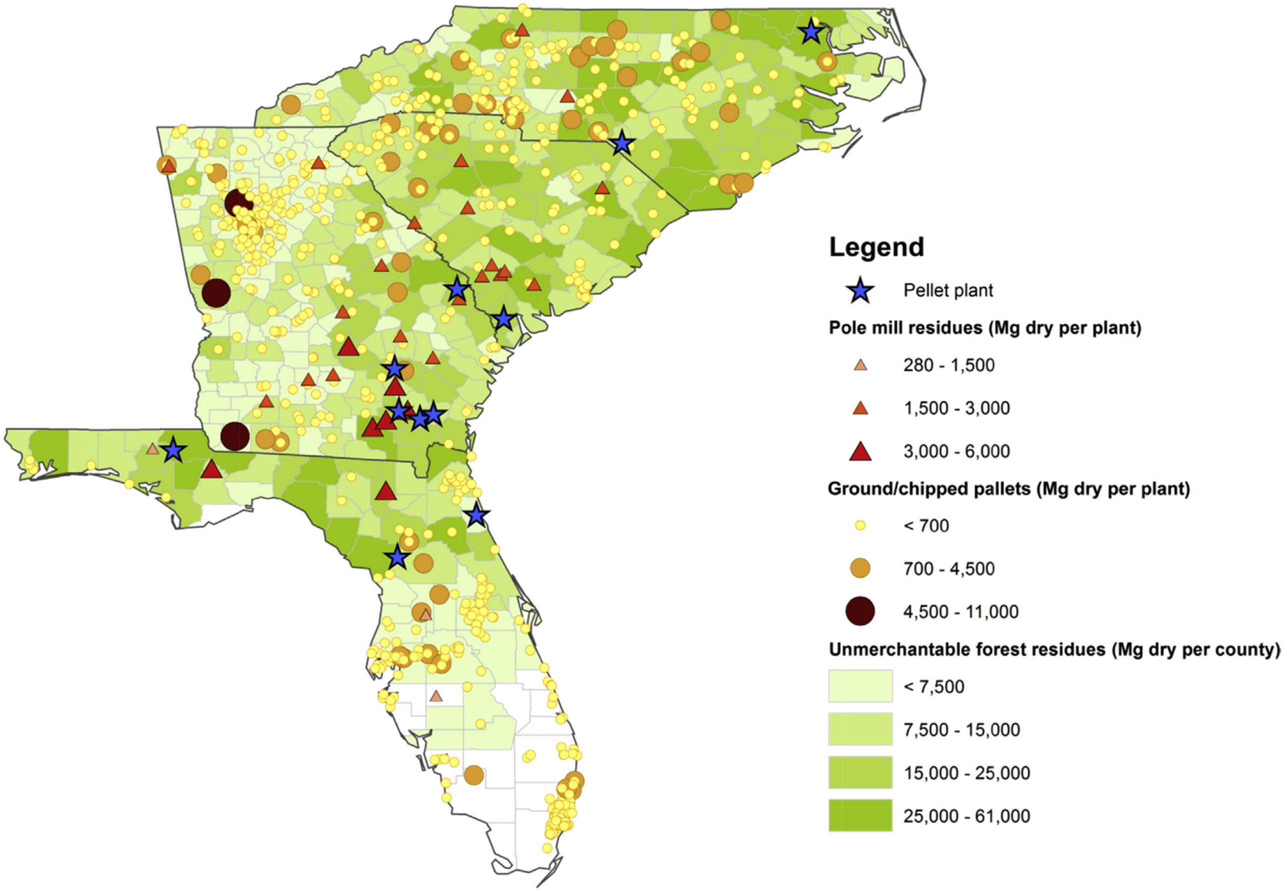

Fig. 3 – The geographic potential (Mg y^{-1} (dry)) of pole mill residues per plant, ground pallets by pallet company and unmerchantable forest residues per county in Florida, Georgia, North Carolina and South Carolina in 2012. Locations of pallet companies: [39]; administrative boundaries: ESRI data and maps [31].

2.4. *Future potential of wood resources*

Projections were made to 2020 using existing, conservative future scenario projections. The future potential of unmerchantable forest residues was assumed to be similar to the growth of 'other removals' published in the updated Billion Ton study [9] of 0.2% (Florida) to 0.3% (Georgia, North Carolina, and South Carolina) from 2012 to 2020. The projections in the updated Billion Ton study were made using RPA timberland projections and exclude the potential of 'other removals' from timberland clearings which are projected to decline with 2.4 M ha by 2030 [9].

The potential of pole mill residues depends on the future production of utility poles in the southeast of the U.S. and emerging markets for pole mill residues. The market for utility poles can increase shortly after natural disasters, but could also decline, e.g. as a result of undergrounding of transmission cables. Because no market outlooks were available for pole industries, future projections were based on the conservative growth rate to 2020 of softwood sawtimber in the U.S. for the Constant Demand, Low GDP scenario of the Southern Forest Resource Project [38]. For similar reasons, this scenario was also used for the future outlook of wood pallet production and the related potential of discarded pallets. Because pallet production is the largest consumer of hardwood lumber in the U.S. and consumes 90% of all lumber and 70% of all structural panels produced for packaging and shipping [7], the growth rate of hardwood lumber to 2020 was used as a proxy for wood pallet production.

3. Results

3.1. *Potential of wood resources*

The combined wood potential of the selected wood sources in the southeast U.S. for this analysis was estimated to be 1.9 Tg y^{-1} available at 22 \$ Mg^{-1} (dry) at roadside or mill gate and more than 5.1 Tg y^{-1} when other residues available at 33 \$ Mg^{-1} (dry) or less are included (Table 3). In theory, the estimated potential of the selected resources in the southeast U.S. is sufficient to produce 4.1 Tg y^{-1} wood pellets (moisture mass fraction: 7%) as calculated from the dry matter losses from feedstock drying and pelletization. In comparison, the total production capacity in the U.S. that is currently operating, proposed or under construction is 10 Tg y^{-1} wood pellets, of which 66% of this capacity is located in southeast of the U.S. [5].

Table 3 – Potential of ‘other removals’, pole mill residues, chipped pallets estimated to be available for wood pellet production in the southeast of the U.S. at 22 $ Mg^{-1} (dry) and the cumulative potential available at 33 $ Mg^{-1} (dry) in 2012 and 2020.

	2012				2020			
	22 $ Mg^{-1} (dry)		33 $ Mg^{-1} (dry)		22 $ Mg^{-1} (dry)		33 $ Mg^{-1} (dry)	
Dry wood potential and lower and upper limits between brackets (Gg y^{-1})								
Unmerchantable forest residues								
Florida	246	(104–423)	739	(312–1269)	247	(104–424)	740	(313–1271)
Georgia	477	(206–848)	1430	(617–2544)	478	(206–851)	1434	(619–2552)
North Carolina	615	(239–1101)	1846	(718–3303)	617	(240–1104)	1851	(720–3312)
South Carolina	278	(98–497)	834	(295–1492)	279	(99–499)	836	(296–1496)
Total	**1616**	**(648–2869)**	**4 848**	**(1943–8607)**	**1 620**	**(649–2877)**	**4 861**	**(1948–8631)**
Pole mill residues								
Florida	13	(10–15)	13	(10–15)	14	(10–16)	14	(10–16)
Georgia	57	(42–67)	57	(42–67)	59	(43–69)	59	(43–69)
North Carolina	5	(4–6)	5	(4–6)	5	(4–6)	5	(4–6)
South Carolina	14	(10–16)	14	(10–16)	14	(11–17)	14	(11–17)
Total	**89**	**(66–104)**	**89**	**(66–104)**	**92**	**(68–108)**	**92**	**(68–108)**
Discarded pallets								
Florida	43	(7–61)	43	(7–61)	48	(8–68)	48	(8–68)
Georgia	78	(12–111)	78	(12–111)	87	(14–124)	87	(14–124)
North Carolina	53	(8–75)	53	(8–75)	59	(9–84)	59	(9–84)
South Carolina	15	(2–21)	15	(2–21)	17	(3–24)	17	(3–24)
Total	**189**	**(30–269)**	**189**	**(30–269)**	**210**	**(33–300)**	**210**	**(33–300)**
All feedstocks								
Florida	302	(120–499)	795	(328–1345)	308	(122–508)	801	(330–1355)
Georgia	612	(260–1026)	1565	(671–2723)	624	(264–1044)	1580	(676–2746)
North Carolina	673	(252–1182)	1904	(730–3384)	681	(253–1194)	1915	(734–3402)
South Carolina	307	(111–535)	863	(308–1529)	310	(112–539)	867	(309–1536)
Total	**1894**	**(743–3243)**	**5126**	**(2038–8981)**	**1923**	**(751–3285)**	**5164**	**(2049–9039)**

The highest potentials are available in Georgia and North Carolina where most pallet recycling companies and pole production mills are located (Georgia, Fig. 3) and the largest amounts of unmerchantable forest residues are generated (North Carolina, Fig. 1). However, variations in the production of unmerchantable forest could increase or decrease the potential substantially. For example, if relatively low amounts of unmerchantable forest residues are generated in Georgia, such as in 1999, the supply potential of unmerchantable forest residues available at roadside at 22 $ Mg^{-1} (dry) would reduce the total potential of dry wood in Georgia by 60%. Note also that pole mill residues and discarded pallets have favorable moisture contents over unmerchantable forest residues (Table 1). Hauling cost and dry matter losses from feedstock drying are therefore higher for unmerchantable forest residues as discussed in Section 3.2.

3.2. *Wood pellet production*

Capital and O&M cost of the pellet production plants are lower for larger plant sizes due to economies of scale. The optimal size of the pellet production plant depends on the geographic supply potential in the wood supply area of the pellet plant. Larger pellet plants require a larger sourcing area to meet the wood fiber demand resulting in longer hauling distances and implied costs. Fig. 4 shows the total economic potential of the selected feedstock types delivered to each of the individual pellet production plants in the four states in 2012. Dry matter losses and implied costs for drying to a moisture mass content of 7% are also included. The scale of the supply curves are limited to 500 Gg y^{-1} dry feedstock, equivalent to pellet production capacities of 404 Gg y^{-1} to 423 Gg y^{-1} wood pellets. At these supply ranges, the cost of dried feedstock increase from 34 $ Mg^{-1} (dry) to 36 $ Mg^{-1} (dry) at the start of the cost-supply curves to 72 $ Mg^{-1} (dry) in Georgia and up to 91 $ Mg^{-1} (dry) in Florida. The future, conservative projections of feedstock potentials hardly affect the cost-supply curves for 2020.

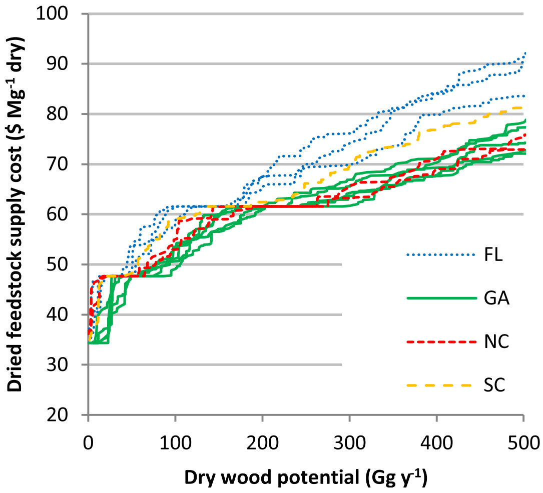

Fig. 4 – Cost-supply curves of all selected wood of all states (Florida: FL, Georgia: GA, North Carolina: NC, South Carolina: SC) delivered and dried at each pellet plant location in each state in 2012 (US$_{2012}$).

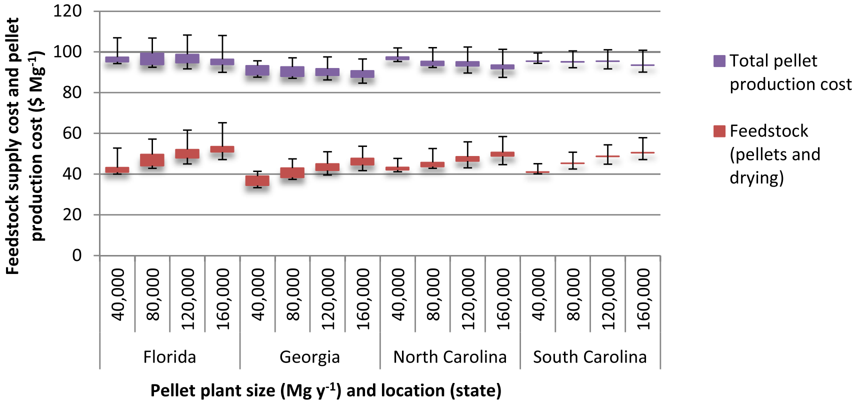

Fig. 5 – Feedstock supply cost (fuel for drying and feedstock for pellets) and total cost of pellet production. The result series show the cost differences between the different locations of pellet plants in each state except for South Carolina, with only one pellet plant location defined (Fig. 3). The error bars show the impact of the lower and upper limits to the feedstock potentials on the wood pellet production cost.

The average capacity of pellet plants in the selected states that are operational, under construction or proposed, is about 300 Gg y^{-1}- pellets [6]. Most new pellet plants are designed for primary sources of wood (pulp wood) with production capacities up to 750 Gg pellets y^{-1} (Georgia). For the low value resources in the present analysis, small pellet production plants were found to be more cost effective than large pellet plants. The cost of feedstock supply, including drying and total pellet production cost for pellet plants with production capacities between 40 Gg y^{-1} and 160 Gg y^{-1} (ar) are depicted Fig. 5. The colored bars show the cost ranges from different plant locations in each state. The error bars show the effect of uncertainty ranges in feedstock supply (Table 3). Under the main supply estimations, pellet production cost were estimated to be 88 $ Mg^{-1} pellets in Georgia and 99 $ Mg^{-1} pellets in Florida. Lower and upper limits in the total supply potentials result in cost ranges of between 85 $ Mg^{-1} to 108 $ Mg^{-1} pellets.

Based on the cost-supply curves for each location and supply assumptions and economies of scale of the pellet plant, the optimal size and location has been calculated for each state as depicted in Fig. 6. The optimal size of the pellet plant and the related pellet production cost can vary strongly depending on the location of the pellet plant and the feedstock supply potential. The optimal pellet production capacity could be as low as 55 Gg y^{-1} if only pole mill residues and discarded pallets are available (d) or as high as 315 Gg y^{-1} for the upper limit of supply potential in South Carolina (c). For the supply scenarios in 2012 (a) and 2020 (f), Georgia has the most optimal location (lowest cost) for pellet production from the selected wood sources. In Georgia, pellets could be produced for 85 $ Mg^{-1} at a pellet plant of 125 Gg y^{-1}- pellet production capacity.

In comparison, FOB (Free on Board) export spot prices of wood pellets in the southeast of the U.S. fluctuated from 140 $ Mg^{-1} to 155 $ Mg^{-1} in 2012 [40]. Note however that the cost estimates in the present analysis exclude the cost of handling and transport between the pellet plant and the ocean export terminal and the cost of loading into a bulk ocean carrier for export and are therefore not directly comparable.

4. Discussion

4.1. *Unmerchantable forest residues*

Statistical data of ‘other removals’ in the U.S. are collected by the USDA Forest Service and reported in the TPO database. There are two main uncertainties in using this database to estimate the potential of ‘other removals’ available for wood pellet production. First, hardly any research has been conducted on the economic potential and logistics to collect these resources in an economic and ecologically sustainable way to produce wood pellets [22]. The technical recovery factor and economic potentials assumed in this study are based on

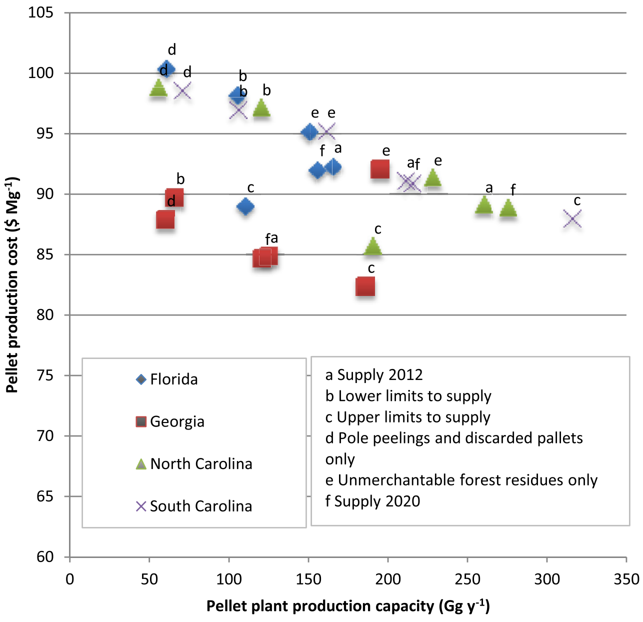

Fig. 6 – Pellet production capacity and cost for optimal plant sizes by state in the southeast of the U.S., scale factor = 0.7, in US$$_{2012}$.

expert estimations [9], but not supported by empirical data from commercial operations or field studies. Secondly, the TPO database does not distinguish between 'other removals' generated from precommercial thinning operations and those generated from land clearing activities. Precommercial thinnings are conducted to improve the quality of the growing stock and could potentially increase the carbon value of managed forests. Land clearing activities, a common practice in the southeast of the U.S., could release substantial amounts of carbon stored in the growing and nongrowing-stock of the trees removed resulting in a net loss of carbon if the land is not replanted with trees. Although recommended by SFI Fiber Sourcing, replanting (reforestation) after land clearing is not obligatory and it is also not legally required by Best Management Practices or Best Harvesting Guidelines in the southeast of the U.S. [41]. For this reason, the Union of Concerned Scientists (UCS) considers 'other removals' not to be a sustainable source of bioenergy [21]. Note however that despite local land clearing activities, on a macro-level, the total forest area remains stable [41].

The potential of unmerchantable forest residues in the present analysis was calculated with assumptions for 'other removals' similar to those of the updated Billion Ton study [9]. However, the potential of 'other removals' available for bioenergy in the U.S. in the updated Billion Ton study is based on 'other removals' in 2003, when relatively low amounts of 'other removals' were generated compared to 2007 (Fig. 1). The potential of 'other removals' is therefore significantly lower (3.3 Tg dry wood in the southeast of the U.S.) than the 4.8 Tg dry wood estimated in the present analysis. Note also that the fluctuations in 'other removals' do not necessarily reflect the minimum and maximum potentials of 'other removals' and fluctuations could be larger if longer time periods would be considered.

4.2. *Pole mill residues*

Although pole, posts and piling mills in the U.S. do report the amount of wood residues produced to the USDA-Forest Service, such information is confidential. The figures used for the amounts of wood residues produced in pole processing mills in the southeast of the U.S. are therefore based on a statistical approach using the total output of wood products produced in post, pole and piling mills by county as reported in the TPO database in combination with the average residue factors for wood and bark of these industries. This method does not distinguish between the production of utility poles and that of other types of posts, poles and pilings because they are reported in a single category in the TPO database. Furthermore, residue factors are provided based on the number of poles produced whereas the TPO database only reports the total mass of posts, poles and pilings produced in these mills. This creates additional uncertainties about the total potential of pole mill residues. However, compared to the global residue factors reported by the FAO [23], the residue factors calculated in the present analysis appear to be plausible.

The present analysis assumes that pole mill residues have no competitive markets other than internal use based on a local market analysis in Georgia [10]. Such markets might exist in other regions in the southeast of the U.S. and if so would reduce the availability of these residues for wood pellet production. These effects would be small because pole mill residues do not add substantially to the total supply potential in the present analysis (Table 3).

4.3. *Discarded transport pallets*

Virginia Tech has a Pallet and Container Industry Production and Recycling Research program that surveys all wooden container and pallet manufacturing industries (NAICS code 32192) in the U.S. [26]. The present analysis used the most recent data from this program (2006) to estimate the amount of discarded wooden pallets available for the production of wood pellets by state. For the geographic potential, the potential in each state has been allocated to companies with NAICS code 32192 based on the number of employees of each company relative to the total employment in the wooden container and pallet manufacturing industries. This resulted in the calculated potential of chipped pallets being highest for larger companies with a high number of employees, regardless if they recycle wooden pallets. In reality, only 55% of these companies are involved in recovery, remanufacturing and repair of wooden pallets [26]. However, the locations of these specific companies are unknown. Furthermore, wooden pallets are also collected at landfill areas where they are often recovered from other types of urban wood wastes [25]. These locations are not considered as a potential location of wooden pallet materials in estimating the geographic supply in the present analysis. Rather, it is assumed that these pallets will be collected by pallet recycling companies if the market for chipped pallet materials will grow.

4.4. *Certification*

To guarantee the sustainability of biomass, several sustainability standards, criteria and certification schemes have been developed [42]. The most widely used voluntary schemes are Green Gold Label (GGL), Laborelec Label and the Drax Power Sustainability principles [43]. Although EU wide mandatory sustainability criteria for solid biomass used for electricity and heat generation are still under discussion, some EU member states, including Belgium and the United Kingdom, have already implemented sustainability requirements in national policy schemes. In the Netherlands, sustainability criteria are still under development, but almost all wood pellets imported from the U.S. to the Netherlands are certified as required by end-users [43]. Because these countries are the main ones importing wood pellets from North America [1], hardly any market exists if the produced pellets cannot be certified.

Sikkema et al. [44] assessed the suitability of existing certification systems for the types of resources selected in the present analysis and identified two suitable systems: GGL and NTA 8080 (Netherlands Technical Agreement). Unmerchantable forest residues and pole mill residues are similar to wood categories that are already widely used for the production of certified wood pellets and could be certified using existing certification schemes. In contrast, no certified wood pellets have been produced from post-consumer wood waste sources yet. Because post-consumer wood wastes are not covered in GGL [44], additional lab tests are required to guarantee that clean wood is being used for the pellets produced from discarded transport pallets. The NTA 8080 recognizes clean post-consumer wood wastes in the classification list of biomass sources for bioenergy purposes: NTA 8003. As long as category A wood is being used (clean unpainted wood), the pellets could be certified with NTA 8080. Until post-consumer wood sources are covered in GGL, NTA 8080 is therefore the preferred certification system [41].

If the wood sources selected in the present analysis are used for electricity generation in Europe, greenhouse gas reductions of over 85% could be achieved [44] which is well above the minimum threshold of 60% as required in the UK and recommended by the EU [45]. Pellets produced from post-consumer wood resources may also be subject to import/export legislations by the Competent Authorities of the Shipment Regulation. Up to now however, category A (clean wood) is exempted from this regulation [41].

4.5. *Technical barriers*

Unmerchantable forest residues are often pushed up and piled before chipping [9] leading to possible contamination with soil and sand. Pole peelings have a high bark content [10]. These contaminants could reduce the life of pellet mill dies resulting in high repair and maintenance costs. Test batches produced from unmerchantable forest residues and pole peelings demonstrate that it is possible to produce pellets that meet the quality requirements of industrial pellets [44]. Impurities in discarded pallets should be avoided before chipping. Nails can and are removed from the chipped pallet stream using magnets, but laminated timber, sometimes used to repair pallets, could result in die clogging. Furthermore, glued laminated wood or painted wood falls under category B wood waste for which legislative and certification barriers to export or import exist [41].

5. Conclusion

The present analysis assessed the potential of alternative, low-value and underutilized wood resources available for wood pellet production in Florida, Georgia, North Carolina, and South Carolina. The selected wood sources included unmerchantable forest residues, pole mill residues and discarded wooden transport pallets. The total dry wood potential of the selected resources was estimated to be 5.1 Tg y^{-1} (dry) and could be processed into 4.1 Tg y^{-1} wood pellets taking dry matter losses for drying into account. These wood sources could therefore contribute substantially to the domestic supply or expected extra-EU imports of wood pellets (15 Tg to 30 Tg wood pellets in 2020).

Because the supply of these wood fiber sources is geographically dispersed and changes substantially over years in the case of unmerchantable forest residues, wood pellet production is most cost effective in relatively small pellet plants. At a cost optimal pellet production capacity of 125 Gg y^{-1}, pellet production cost are calculated at 85 \$ Mg^{-1} in Georgia and up to 92 \$ Mg^{-1} in Florida. In 2012, FOB spot prices of conventional wood pellets southeast of the U.S. were between 140 \$ Mg^{-1} and 155 \$ Mg^{-1}. Although FOB spot prices cannot be compared directly with pellet production cost at plant gate, it is expected that wood pellets from the selected resources in the present study can become an economically attractive case for export to Europe.

Discarded pallets and other types of post-consumer waste wood have the lowest market value, but the potential is limited and for some post-consumer wood sources, advanced cleaning methods are required. The potential of unmerchantable forest residues in the southeast of the U.S. is large. However, both the potential that can be mobilized at competitive costs, and the potential that can be removed under sustainability restrictions, are still uncertain. More research is therefore required to quantify the economic and sustainable potential of these wood resources.

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REFERENCES

[1] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade – an analysis of volumes, policies, and market factors. Renew Sust Energy Rev 2012;16(5):3176–99.

[2] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013;7(1):24–42.

[3] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: global woody biomass trade for energy. In: Martin J, Goh CS, Faaij A, editors. International bioenergy trade. Springer; 2013.

[4] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global wood pellet industry market and trade study. IEA bioenergy task 40: sustainable international bioenergy trade. 2011. p. 190.

[5] SELC. Biomass energy in the south – MAPS [internet]. 2013 [cited 2013 July]. Available from:, http://www.southernenvironment.org/cases/biomass_energy_in_the_south/maps/.

[6] BBI International. Biomass magazine – pellet plants – USA [internet]. Grand Forks, ND: BBI International; 2013 [cited 2013 January]. Available from:, http://www.biomassmagazine.com/plants/listplants/pellet/US.

[7] McKeever DB, Howard JL. Solid wood timber products consumption in major end uses in the United States, 1950–2009-a technical document supporting the forest service 2010 RPA assessment. United States Department of Agriculture Forest Service; 2011.

[8] Hess JR, Jacobson JJ, Cafferty K, Vandersloot T. International energy agency (IEA) task 40 sustainable international bioenergy trade: securing supply and demand country report 2010-United States. Idaho Falls, ID: Idaho National Laboratory, Kansas State University; 2010.

[9] Perlack RD, Stokes BJ, (Lead Authors). U.S. billion-ton update: biomass supply for a bioenergy and bioproducts Industry. Oak Ridge, TN: Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy under contract DE-AC05-00OR22725; 2011, August [227 p. ORNL/TM-2012/224].

[10] Meyers S. Identifying sources of woody biomass for the purpose of pelletizing. Baxley, Georgia: Fram Renewable Fuels, LLC; 2011.

[11] Mazeika Bilbao A, Carrano AL, Hewitt M, Thorn BK. On the environmental impacts of pallet management operations. Manag Res Rev 2011;34(11):1222–36.

[12] Franklin Associates. Life cycle inventory of wood pallet systems – final summary report. Prairie Village, Kansas: Franklin Associates – A Division of ERG; 2007.

[13] Bentley J. Background data for the timber product output (TPO) database: mill residue factors. Knoxville, TN: USDA Forest Service; 2012, February. SRS-FIA.

[14] Johnson TG, Bentley JW, Howell M. The south's timber industry – an assessment of timber product output and use, 2007. Asheville, NC: U.S. Forest Service; 2009.

[15] White EM. Woody biomass for bioenergy and biofuels in the United States – a briefing paper. USDA Forest Service Pacific Northwest Research Station; 2010. PNW-GTR-825.

[16] Smith WB, Miles PD, Perry CH, Pugh SA. Forest resources of the United States – a technical document supporting the forest service 2010 RPA assessment. USDA Forest Service; 2009. WO-78.

[17] Vis MW, Berg Dvd. Harmonization of biomass resource assessments – volume I: best practices and methods handbook. 1st ed. Biomass Energy Europe (BEE); 2010.

[18] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials-methodological lessons from review of state of the art bioenergy potential assessments. Renew Sust Energy Rev 2012;16(9):6598–630.

[19] Conner RC, Adams TO, Johnson TG. Assessing the potential for biomass energy development in South Carolina. Asheville: United States Department of Agriculture Forest Service – Southern Research Station; 2009.

[20] USDA Forest Service. Timber product output (TPO) reports [internet]. Knoxville, TN: U.S. Department of Agriculture Forest Service – Southern Research Station; [N.d.]. [cited 2012 February]. Available from: http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php.

[21] UCS. The promise of biomass clean power and fuel – if handled right. Union of Concerned Scientists (UCS); 2012.

[22] Walsh M. Bioweb – other removals [internet]. Sun Grant Initiative and the University of Tennessee; 2008 [cited 2013 July]. Available from:, http://bioweb.sungrant.org/Technical/Biomass+Resources/Forest+Resources/Other+Removals/Default.htm.

[23] UN. Forest product conversion factors for the Unece region – Geneva timber and forest discussion paper 49. Geneva, Switzerland: United Nations – United Nations Economic Commission for Europe (UNECE)/Food and Agriculture Organization of the United Nations (FAO); 2010. ECE/TIM/DP/49.

[24] Araman P. Additional background information to the updated pallet and container industry production and recycling research report. Blacksburg, Virginia: Virginia Tech – Department of Wood Science and Forest Products; 2008. 2012.

[25] Bush RJ, Corr DT, Araman PA. Fewer pallets reaching landfills, more are processed for recovery. Pallet enterprise – pallet and sawmill magazine. 2001; May. p. 18–21.

[26] Bush RJ, Araman PA. Updated pallet and container industry production and recycling research. Blacksburg, Virginia: Virginia Tech – Department of Wood Science and Forest Products; 2008.

[27] LexisNexis. LexisNexis Company Dossier – NAICS code 32192 2012. [cited 2013 July].

[28] Buehlmann U, Bumgardner M, Fluharty T. Ban on landfilling of wooden pallets in North Carolina: an assessment of recycling and industry capacity. J Clean Prod 2008;17:271–5.

[29] Buehlmann U, Araman P, Bush R. Pallet re-use and recycling saves high value material from landfills. Engagem Matters 2010;2(1). 8, 10.

[30] NCDENR.. Wooden pallets [internet]. Raleigh, NC: N.C. Division of Environmental Assistance and Outreach; 2012 [cited 2012 August]. Available from:, http://portal.ncdenr.org/web/deao/recycling/wp.

[31] ESRI. Data and maps for ESRI ArcGIS – North America detailed streets [DVD]. 2010.

[32] Staudhammer C, Hermansen LA, Carter D, Macie E. Wood to energy: using southern interface fuels for bioenergy. USDA Forestry Service – Southern Research Station; 2011. p. 89.

[33] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenergy 2004;27(6):671–93.

[34] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008;33(8):1206–23.

[35] Pirraglia A, Gonzalez R, Saloni D. Techno-economical analysis of wood pellets production for U.S. manufacturers. BioResources 2010;5(4):2374–90.

[36] Mani S, Sokhansanj S, Tagore S, Turhollow AF. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant – part 2: cost of heat and power generation systems. Biomass Bioenergy 2010;34(3):356–64.

[37] Obernberger I, Thek G. The pellet handbook – the production and thermal utilisation of biomass pellets. London, Washington DC: Earthscan. 2010.

[38] Wear DN, Greis JG. Southern forest future project: summary report. Asheville, NC: USDA-Forest Service, Southern Research Station; 2011. p. 54. Gen. Tech. Rep. SRS-GTR-168.

[39] Steppleton C. U S. wood-using mill locations – southern mills [internet]. Asheville, NC: USDA Forest Service Southern Research Station; 2005 (2009 by email request). [cited 2012 February]. Available from:, http://www.srs.fs.usda.gov/econ/data/mills/.

[40] Argus. Argus biomass markets – weekly biomass markets, news and analysis. May 2012, July 2012, October 2012, November 2012. 2012.

[41] van Dam J, Ugarte S, Spijkers S, Sikkema R, Schipper E. Inbio – B project: the use of post-consumer waste wood for energy pellets in Europe. SQ Consult, Control Union; 2013.

[42] van Dam J, Junginger M, Faaij APC. From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. Renew Sust Energy Rev 2011;14(9):2445–72.

[43] Goh CS, Junginger M, Joudry J, Chum H, Pelkmans L, Smith CT, et al. Impacts of sustainability certification on bioenergy markets and trade – strategic inter-task study: monitoring sustainability certification of bioenergy. IEA Bioenergy; 2013, February. p. 61.

[44] Sikkema R, Meyers S, Schipper E. Sustainable import of pellets from the United States (Inbio A project). Zwolle, The Netherlands: Control Union; 2012. p. 28.

[45] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling – report from the commission to the council and European parliament. Brussels, Belgium: COM; 2010, February. p. 11 [final].